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THESIS

A SPECTROSCOPIC INVESTIGATION OF MOVING STRIATIONS IN A NEON GLOW DISCHARGE

by

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STRIATIONS IN A NEON GLOW DISCHARGE

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ABSTRACT

An investigation of moving striations in a neon glow discharge, using a Baird-Atomic Plasma Spectrograph, was conducted to determine the time difference in the occurrence of the maxima of the neon spectral lines. Data are presented in the form of oscilloscope trace photographs. These photographs were analyzed to determine the time differences in the occurrence of the maxima of the 6402A and 5944A lines and the 6402A and 6929A lines of neon. Discharge tube pressures of 1.4, 2.74 and 4.45 torr were used with a variation of discharge tube current at each pressure. No time differences were observed within an uncertainty of approximately 15 microseconds.

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CHAPTER I

1. Introduction

Direct current glow discharges have been observed for many years. The name striations has been given to the alternate light and dark areas found in the discharges. Standing striations, which are visible to the naked eye, were discovered by Abria in 1843. Moving striations, which move with such a high velocity that they are not visible to the naked eye, were discovered about 30 years later. Despite the long history of the striations in gas discharges, few of these phenomena were understood until the last decade.

For many years moving striations were observed with a rotating mirror. Now the striations may be observed more effectively with a photomultiplier tube and oscilloscope. Despite the improvement in experimental technique, and the recent increased interest in this phenomenon, many questions are still unanswered. The interaction between the atoms, ions and electrons in the gas discharge is very complicated and presents a formidable challenge. The problem is further complicated by the fact that the discharge phenomenon is highly dependent on the tube geometry, gas pressure, gas purity and discharge current.

2. Gaseous Discharges

If an electric field is applied between two electrodes in a glass tube containing an inert gas such as neon, a discharge may be started. Prior to the initiation of the discharge a very small current exists in the tube. As the

voltage is increased a critical voltage is reached at which the current increases many fold. This voltage is called the sparking potential. After the discharge has started, the potential drop across the tube decreases and the discharge is characterized by the emission of light from the tube.

One might expect, since a direct current voltage is applied across the tube, that the discharge would be homogeneous. However, this is not always the case. If the gas pressure in the tube is on the order of a few torr, the discharge can be described as consisting of regions of low and high light intensities. Adjacent to the cathode is the Aston dark space, followed by a high intensity region, the cathode glow; this is followed by the cathode dark space and then the negative flow; then comes the Faraday dark space, the positive column, the anode glow and finally the anode dark space. The glow discharge is depicted in figure 1.

A discharge may be operated under "hot" or "cold" cathode conditions. The hot cathode condition is obtained by heating the cathode with a filament as is done in a similar manner in an electronic vacuum tube, the cathode in this case being some kind of efficient thermionic emitter. A tungsten filament is commonly used in a discharge tube. In cold cathode operation, electrons are produced primarily by ion bombardment of the cathode, which may be a nickel plate. Figure 1 shows that the large electric field in the vicinity of the cathode accelerates the ions into the cathode.

Figure 2 shows a typical current-voltage characteristic for a cold cathode tube. Below V_s, the sparking potential, essentially no current passes through the tube. When a voltage is greater than V_s, the current in the tube may be increased by decreasing the amount of series resistance. As the resistance is decreased, the current increases along the region of the characteristic from a to b. In this region the current is very low, on the order of a microampere, and the light intensity is very feeble. Further reduction of the resistance increases the current over a large range of values with little change in the voltage across the discharge tube. The conditions that exist for this range of currents (b to c on the curve of figure 2) are referred to as the "normal" conditions and they are determined uniquely by the type of gas and cathode material used. Further increase in the tube current beyond the normal range will occur only at the expense of an increase in the voltage.

As electrons are emitted from the cathode they are accelerated towards the anode, gaining energy from the electric field. The electrons must be accelerated through a finite distance before they gain enough energy to excite the atoms of the filling gas to their lower excitation levels; this accounts for the Aston dark space near the cathode. The cathode glow occurs at the point in the discharge where the electrons first have enough energy to excite the neutral atoms.

Suppose that prior to the initiation of the discharge the individual concentrations of the electrons and positive ions

were equal at all points between the cathode and the anode. When the potential is applied between the cathode and anode, the electrons are accelerated towards the anode and the ions (if any exist) are accelerated toward the cathode. The electrons, however, move much more rapidly than the positive ions and a positive space charge is produced in front of the cathode. Although new ions and electrons are continually produced in the discharge, the positive space charge maintains its position in front of the cathode. This region of positive space charge is the cathode dark space and it is dark for the following reasons. Line spectra are not observed because the electrons entering the dark space have an energy too high for a high probability of excitation to occur. Band spectra due to ion-electron recombination do not occur because the diffusion relaxation time for diffusion to the walls is much shorter than the relaxation time for recombination and therefore recombination does not occur.

Figure 1 shows that the greatest potential drop in the tube occurs between the cathode and the negative ~~f~~glow. It is well known that for a parallel plate capacitor, with no space charge between the plates, the voltage drop across the capacitor is linear. However, if a positive space charge exists between the plates, this charge screens the positive plate from the negative plate. Thus the voltage drop across the plates is non-linear, with the largest part of the drop occurring between the negative plate and the positive space charge. In a loose sense one may consider the discharge tube to be a

capacitor. The positive space charge of the cathode dark space shields the anode from the cathode and the largest potential drop occurs between the cathode and the negative glow. This drop in potential is called the cathode fall.

The magnitude of the cathode fall and the length of the cathode dark space are functions of the filling gas used, the gas pressure and the cathode material. The cathode fall may be reduced, and the current density increased, in the tube, by increasing the secondary emission from the cathode. This may be done, for example, by flooding the cathode with photons of sufficient energy to produce electrons through the photoelectric effect.

The average energy of the electrons is reduced in collisions as they pass through the negative glow. This is evident from the observation that spectral lines arising from the higher energy levels appear nearest the cathode. Electron and ion concentraion are highest in the brightest part of the negative glow. This concentration is normally higher than in any other part of the discharge and may be as high as 10^{11} per cubic centimeter, perhaps ten to one hundred times the concentration that occurs in the positive column. The maximum concentration within the negative glow falls off rapidly in the direction of both the anode and the cathode.

The electric fields are always found to be small in the Faraday dark space. (In fact, the electric field is reversed in many low pressure cases. However, it has been shown that under these conditions the concentration gradient is sufficient to cause the necessary transport of electrons to the

anode.) The main current between the cathode dark space and the negative glow is probably sustained by electrons coming from the cathode dark space; the flow of any positive ions in the opposite direction is small compared to the electron flow. The current between the negative glow and the Faraday dark space is carried largely by diffusion of slow electrons due to the concentration gradient.

The anode glow is often found to be unstable. This instability may take the form of an oscillation about a mean position or an oscillation between two different forms. Large anode glows are sometimes found to consist of a rotating pattern of small regularly arranged spots, whose speed of rotation is sometimes slow enough to be seen with the naked eye. These instabilities may be supressed by the use of an auxiliary discharge at the anode.

If the tube length is relatively long compared to the tube diameter, the major part of the discharge will consist of the positive column, a weakly ionized plasma. (The term plasma was first applied to the positive column of a gas discharge by Irving Langmuir. He used this term to convey the idea that the positive and negative charge densities were approximately equal in the positive columns of the discharges with which he was working.)

The positive column is maintained by a small residual electric field which accelerates the electrons, replacing the energy they lose through collisions, such that the rate of production of ions by electron impace on neutral atoms is

balanced by the loss of ions by diffusion to the walls. Actually ions may be lost to the tube walls in two ways, by diffusion and by free fall. The difference in the two cases is in the length of the mean free path. In the case of diffusion, the mean free path between collisions for the ions is short enough that the ions suffer many collisions enroute to the wall, while in the free fall case the ion mean free path is so long that the ion reaches the wall without making any collisions. For the pressures used in our experiment the ion mean free path was on the order of 2.5×10^{-3} cm. Since the tube radius was 3 cm the ion loss was due to diffusion. In this tube the pressure would have to be on the order of 1.66×10^{-3} torr for the free fall condition to prevail.

The longitudinal potential gradient within the positive column has been found to approach a limiting value as the tube diameter is increased. This limiting value depends only on the nature and pressure of the gas. The positive column is usually more luminous in narrow tubes. However, for a given tube diameter, the brightness is a function of gas pressure, reaching a maximum as the pressure is increased.

Although one might expect that the light intensity would be uniform within the positive column, many observations have shown that for a wide range of conditions the light intensity is not uniform. That is, the positive column itself may consist of striations (dark and light regions). Striations are well known to appear in diffusion maintained positive columns but their occurrence in the free fall case is not well

established. As previously mentioned these striations may be moving or stationary. This experiment is concerned with the phenomenon of moving striations.

3. Moving Striations

A. Upper and Lower Critical Currents

Moving striations are spontaneously present in the normal operation of cold cathode inert gas glow discharges. Pupp (22) found that for a constant gas pressure condition, if the current was increased sufficiently, a striation-free positive column could be obtained. This current limit at which the striation-free region occurs is called the upper critical current. The value of this current is found to be a function of the discharge parameters. For a convenient representation, the upper critical current may be plotted on a current (i) versus pressure (p) diagram. The resulting curve separates the i-p space into regions where moving striations do occur spontaneously and where they do not. Pupp made measurements of the upper critical current for the inert gases helium, neon, argon and krypton. He found the relation between current and pressure approximately represented by the empirical relationship

$$i_c = \frac{c}{p}$$

where c is a constant for each gas.

Further measurements have shown the value of the upper critical current to be sensitive to variation in tube diameter (2,3). Establishing an experimental criterion for the determination of the upper critical current is not as simple as it

might seem. In some gases, particularly neon, the striations do not disappear from all parts of the positive column simultaneously. As one might expect, since the value of critical current obtained depends on the position in the column at which striations are observed, the results of various observers fail to agree exactly. The reason the striations do not disappear simultaneously has been tentatively ascribed to the amplification of the wave of stratification (see section 5 of chapter I), and the feedback to the cathode through the external circuit.

There is also a lower critical current. For sufficiently low values of current and pressure, helium, neon and argon display a homogeneous positive column. The current at which this condition occurs is called the lower critical current for slow striations. The region, for which the positive column is homogeneous, is relatively small. Below this region there exists a region of fast moving striations with frequencies on the order of 20 KHz. No lower limit for fast striations has been found.

4. Factors Influencing Moving Striations

A. External Circuit

The use of a large variable resistor in series with the discharge tube was discussed in section 2. It has been known for a long time that while the circuit parameters do not define the striation frequency, nevertheless oscillations in the external circuit may couple with the striations (26). Pekarek (15) has shown experimentally that the amplitude and

frequency of the moving striations are modified slightly by changes in the feedback characteristics of the external circuit. He modified the feedback loop by putting a capacitor in parallel with the circuit resistor. If the discharge current is maintained constant while the resistance is changed, the striations are also modified in frequency and amplitude. These effects are observed only near the threshold of self-excitation of the striations.

B. Tube Radius

The effect of discharge tube diameter on moving striations has been dramatically demonstrated in a single tube consisting of sections of different diameters, as shown by Cooper and Oleson (2). This technique has the advantage that gas pressure, total current and external circuit are common to all sections of the tube while the striations in each section of the tube are subject to the same effects of current fluctuations and external circuit oscillations, each section of such a tube has its own characteristic set of striations with a transition region occurring at the junction between sections of different diameter. The measured striation velocity, wavelength and frequency of each section of the tube compare closely with the results obtained in a uniform tube of the same diameter. The values obtained from adjacent sections of the tube were not necessarily integrally related.

Several additional experiments have been performed to determine the dependence of the striation wavelength on tube radius (1, 9, 10). Experiments have been made in tapered

tubes using both neon and argon gas. However, the results have been in conflict and no general relationship between striation frequency and tube radius can be considered to be established.

C. Tube Length

It has been shown by Zaitsev (21) that for a constant discharge current, the amplitude and frequency of striations vary periodically as the length between the electrodes is varied. The spatial period of this variation was found to be equal to the striation wavelength. The frequency variation with change in tube length was found, in neon, to be approximately sinusoidal while this variation was approximately sawtooth in argon. Gertzenstein and Potemkin (8) explain this effect by invoking the condition for positive feedback, namely that the total phase shift in the loop must be an integral multiple of 2π for an auto-oscillating system. Therefore as the discharge length is changed in a self-excited moving striation discharge, the striation wavelength must change in order to keep the total circuit phase shift equal to $2\pi m$, where m is an integer.

D. Miscellaneous Geometrical Effects

Location and shape of the electrodes can affect the moving striations. Zaitsev (27, 28) has stated that cathode oscillations are less likely when the cathode is located in a side-arm and that anode oscillations are less likely if the anode is in the shape of a curved cone of revolution. In addition the location of the electrodes with respect to the

sides of the glass tube, evaporated electrode material on the tube walls and material deposited on the tube walls by sputtering may affect the striations. Electrode material deposited on the tube walls affects the space charge electric fields at the electrodes.

5. Striation Production Mechanisms

Numerous experiments studying moving striations have been performed and in many cases the results have led to conflicting theories. Donahue and Dieke (6) postulated that metastable states of the atoms in the discharge are necessary for the production of moving striations while Pekarek and Krejci (16) stated that moving striations may occur in the absence of metastable states. Oleson and Cooper (14) give a review of the more recent and significant theories.

A brief description of two different mechanisms that could explain moving striations follows. The first is that postulated by Donahue and Dieke (6), the second by Pekarek and Krejci (16).

A. Donahue and Dieke

Donahue and Dieke explained the moving striation propagation mechanism on the basis of several assumptions. Consider that at some point X_1 in the positive column there exists a positive space charge. Suppose that on the cathode side of this space charge there exists a region X_2, highly populated by atoms in metastable states. Further suppose that on the cathode side of this second region there exists a region X_3 of maximum rate of production of metastable states.

(If electrons traveling from the cathode reach region X_3 with an energy sufficiently high, excitation into the upper excited states occurs. Subsequent transitions downward fill the metastable states. A maximum rate of production of metastable states occurs at X_3.) Now the electrons leave X_3 with reduced energy but are accelerated as they approach X_2. When the electrons encounter the atoms in metastable states at X_2 they excite them to higher levels, because the required energy is much smaller than if the atoms are in the ground state, and in many cases cause ionization. The electrons then proceed to the region of positive space charge where recombination and diffusion occur. It is apparent that the positive space charge has now moved to X_2 and the high population of metastable states has moved to X_3. The process being continuous, the region of positive space charge moves toward the cathode and the striations propagate from the anode to the cathode in agreement with observations in inert gases.

B. Pekarek and Krejci

Pekarek first postulated his theory of the wave of stratification in 1957. He assumed that a perturbation in the homogeneous positive column of a discharge caused a temporary increase in the electron temperature at the point of disturbance. Consequently an increase in the number of inelastic collisions between electrons and neutral atoms occurs. Two processes are now possible. In process I the electron temperature is assumed to be sufficient to cause direct ionization of the neutral atoms, resulting in an increase in

production of charged particles of both signs. The electrons because of their higher mobility, move away from the initial disturbance more rapidly than the positive charges, leaving a positive space charge in the vicinity of the initial disturbance. This space charge eventually decays through diffusion. In process II the change in electron temperature produces metastable atoms, rather than ions, which are subsequently ionized, with a positive space charge being formed in the same manner as in process I.

Consider the initial disturbance in electron temperature to occur at some point X_1 in the tube. In both processes a positive space charge is created which generates a local electric field opposing the applied electric field. Therefore, on the anode side (position X_2) of the positive space charge there is a region of decreased electric field and lowered electron energy. Hence a dark space is formed in which the lowered electron temperature results in a deficiency in ions and metastable atoms and in the formation of a negative space charge. This negative space charge causes a local increase in the electric field which adds to the applied field, thereby increasing the electron temperature to the anode side of the negative space charge. This increase in electron temperature causes process I or II to occur again, producing a light region. Therefore, if an initial disturbance occurs at the cathode, a packet of light and dark regions called a packet of stratification propagates down the tube from the cathode to the anode. In the case of self-excited striations

(when the amplification around the loop is greater than one), the packet of stratification causes a disturbance at the anode which is transmitted through the external circuit back to the cathode where another packet of striations is formed. This process repeats itself and a continuous wave of stratification is formed. In this model, the moving striations move within the packet of stratification in the direction opposite to the motion of the packet. This is explained as follows. Consider, once again, the initial perturbation to the electron temperature. The increase in local electric field strengthens the applied electric field on the cathode side of the disturbance, creating a light region. This increase in electric field causes an increase in the electron temperature further toward the cathode which causes another increase in the electric field and so on. In this manner the light region is propagated toward the cathode. Now consider the point X_2, the position at which the initial decrease in electron temperature occurred. On the cathode side of X_2 the electric field is decreased causing a decrease in electron temperature further toward the cathode and hence the dark region originating at position X_2 is propagated toward the cathode. In a similar manner other successive perturbations in the electron temperature will propagate light and dark regions toward the cathode; that is the striations move toward the cathode.

Equations representing processes I and II have been written and solved for the case where the initial disturbance is a Dirac delta-function. The differential equation representing

process I is given by

$$\frac{d\theta_\nu}{dt} + a\theta_\nu + aA\theta_{\nu'} = 0 \qquad (1)$$

Process II is represented by

$$\frac{d^2\theta}{dt^2} + (a+b)\frac{d\theta_\nu}{dt} + ab\theta_\nu + B_0\theta_{\nu-1} = 0 \qquad (2)$$

where,

θ = electron temperature.

a = time constant for space charge decay by diffusion.

b = time constant for metastable state decay by two stage ionization.

A and B_0 = amplification parameters

ν represents the ordering of successive maxima and minima in the electron temperature. The maxima are denoted by ν = 0, 2, 4,...., the minima by ν = 1, 3, 5, ...

The exact solution to equation (1), assuming a delta-function input, is

$$\Theta(z,t) = A^{\frac{2(z+vt)}{\lambda}}\alpha c\left\{(\alpha t)^{\frac{2(z+vt-1)}{\lambda}}\right\}\frac{\cos\left[\pi\frac{2(z+vt)}{\lambda}\right]}{e^{\alpha t}\,\Gamma\left(\frac{2(z+vt)}{\lambda}\right)} \qquad (3)$$

where,

z is the distance down the axis of the tube.

v is the velocity of propagation of the disturbance in the electron temperature.

λ is the distance between successive peaks in the electron temperature distrubance.

c is the amplitude of the initial delta-function disturbance.

Γ ( ) is the gamma function of the argument in the parenthesis

This rather complicated expression consists of two parts, a cosine term which is a traveling wave term and a complicated time-dependent amplitude term which modifies the traveling wave. Figure 3 shows a plot of equation (3). Analysis of this equation shows that the wave of stratification travels in the negative z direction where the positive z direction is defined as the direction from anode to cathode. If it is assumed that the light intensity variations are directly proportional to the changes in the electron temperature, then equation (3) will show the changes in light intensity at an arbitrary ν^{th} place.

Pekarek (17) has conducted experiments in neon and verified some of the predictions of his theory on the wave of stratification. In particular he found the time for the maximum of the wave of stratification to arrive at a given point in the positive column, measured from the instant of excitation, to be in good agreement with the theory. However, he found that the time width at a given point in the positive column, corresponding to the time difference at which the amplitude is one half maximum, was larger than predicted by theory.

Pekarek and Novak (18, 19) have shown experimentally that there can exist three waves of stratification, the slow wave (p-wave), the fast wave (r-wave) and a faster wave

(s-wave). The wave velocities are dependent on the relaxation times involved in the mechanisms causing the waves. Process II (previously described) involves metastable states and their relatively slow diffusion rates and therefore seems to correlate with the slow wave. Process I involving single stage ionization would seem to be applicable to the r and s-waves. A comparison of the relaxation times of the two faster waves has shown that the relaxation time of the r-wave corresponds to the diffusion lifetime of atomic ions (Ne^+) while the relaxation time of the faster s-wave corresponds to the diffusion of molecular ions (Ne_2^+). (8)

An important difference in the two mechanisms that have been presented is that the Donahue and Dieke model requires the presence of metastable states while the Pekarek and Krejci model does not require metastable states but does allow them.

6. Previous Spectroscopic Investigation of the Striations

Several experiments have been performed in which the spectrum emitted by the moving striations has been studied. (Several spectroscopic studies of an argon discharge were made at the Naval Postgraduate School during the period 1956 to 1958.) In some experiments the results have been inconclusive, while the results of some others have been contradictory. For example, Donahue and Dieke found the lower excitation potential lines in mercury-argon to lead, while Rutscher found the lower excitation lines in neon to lag. The present work was conducted to see if conclusive results could be obtained in neon by repeating Rutscher's experiments.

Donahue and Dieke (6) observed in a mercury-argon discharge that the maximum of the 2537A line, of low excitation potential, leads the maxima of the lines of higher excitation potential. Rutscher (24) observed 15 spectral lines in neon and noted that the maxima of the higher excitation potential lines appeared to lead the maxima of the lower excitation potential lines.

At this point it is in order to define the term "phase shift" as it will be used in this paper. Phase shift is defined to be the time difference between the occurrence of the maxima of the two spectral lines being compared.

The mechanism postulated by Donahue and Dieke for the production of moving striations was postulated to explain the phase shift that Donahue and Dieke observed in the mercury-argon discharge. Their model required that two-stage ionization take place, with the higher levels being excited from lower metastable states. Since the lower excitation levels are excited first, one might expect the maxima of lower excitation lines to occur first, while Rutscher found the opposite results in neon discharges. On the other hand, the Pekarek and Krejci model does not require the presence of metastable states and is more general in its application but requires a somewhat detailed knowledge of parameters in the discharge which are frequently not available.

CHAPTER II

1. Experimental Techniques and Procedures

A Baird-Atomic Plasma Spectrograph was used to resolve the various spectral lines of the neon gas discharge. The spectrograph setting used covered the range of 4800A to 7600A, which included all lines of interest, although the spectrograph has an overall range from 2000A to 22630A.

The discharge tube was orientated perpendicular to the spectrograph optical axis, with the spectrograph entrance slit aligned approximately with the center of the discharge tube. An aperture of about 6 mm width was placed near the discharge tube to provide spatial resolution of the discharge. The light from the discharge tube was focused onto the 750 micron entrance slit of the spectrograph by a quartz lens.

Two photomultiplier tubes were mounted on a rack at the front of the spectrograph. Two tubes were used so that two spectral lines could be compared simultaneously. In order to facilitate the location of the photomultiplier tubes on the lines, a paper mask was made which had slits cut at the positions of the spectral lines. Because the faces of the photomultiplier tube mounts were so large that light from more than one spectral line illuminated the face of the tube, another single slit mask of smaller dimension was made so that only the light from one line reached the face of the tube. Due to the small separation of most of the spectral lines, adjacent lines could not be compared (with one exception). The 5400A line was separated from its adjacent line

sufficiently to allow comparison, but it was too weak to use. Appendix I shows the neon lines which were of interest.

The outputs of the photomultiplier tubes were fed into a Tektronix model 547 dual trace oscilloscope. The oscilloscope was triggered by a separate photomultiplier tube which looked directly at the discharge tube.

Since the object of the experiment was to compare the time at which the various spectral lines reached their maximum intensity, it was important that the photomultiplier tubes have similar responses. Two tubes were selected from a group of six. The tubes were checked for frequency response by locating a strobe light near the grating in the spectrograph. The photomultiplier tubes were connected to the oscilloscope and the output signal observed with the strobe light operating at 400 Hz. Figure 4 indicates that the signals reached their maxima at the same time. The horizontal sweep speed is 5 microseconds per cm. A 2 microsecond phase shift would easily be observed.

The effect of varying the photomultiplier tube signal cable length was also studied. It was found that varying this cable length did not change the time at which the signal peaked but that it did change the shape of the decaying trace. It was also noted that longer cables resulted in a serious decrease in signal strength. To minimize these effects, the cables were made the same length and as short as possible, about a meter in length.

The discharge was operated cold cathode with an auxiliary discharge at the anode. Preliminary measurements were then made over a range of discharge parameters. The data were recorded in photographs taken with an oscilloscope camera. The initial results were entirely inconclusive because the signals were too noisy to be able to tell where the maxima occurred. This was true for a variety of discharge tube pressures and currents. The possibility of cooling the photomultiplier tubes was considered. It was expected that the photomultiplier tube noise would be decreased to an unknown extent. The technique of blowing liquid nitrogen across the cathode of the tube was tried with the results shown in figure 5. The bottom picture shows the 6402A trace (bottom trace) and the 5944A trace before cooling the photomultiplier tubes. Note that the signals are unusable. The top picture shows the dramatic change in the same signals after cooling. The noise is greatly reduced and the signal in one case is increased. The signal peaks are in the same relative positions as in the bottom picture. Discharge tube parameters and oscilloscope settings were exactly the same for both pictures.

The cooling of the photomultiplier tubes was simply accomplished as follows. A concentric double length of tubing is put into a 50 liter dewar. The tubing is held tightly in the dewar by thick rubber tubing at the mouth of the dewar. The inner metal tubing is connected by plastic tubing to a bottle of dry nitrogen gas. The outside annular

tubing is terminated in a T connection. Two pieces of plastic tubing, connected to the T, lead the liquid nitrogen from the dewar to the photomultiplier tube faces. The apparatus is shown in figure 6. The dry nitrogen gas is used to pressurize the dewar thereby forcing the liquid nitrogen out. The liquid nitrogen cooled the face of the tubes without causing condensation on them.

CHAPTER III

1. Analysis of Data

Rutscher (13) studied the phase differences of the spectral lines of a neon gas discharge. His experimental technique was similar to ours. Rutscher used a Zeiss mirror monochromator to study the individual spectral lines, measuring the monochromator light output with a Zeiss Jena SEV (secondary electron multiplier). The output of the SEV was fed through an A-C amplifier to an oscilloscope. In order to compare two spectral lines a photograph of the trace of the first line was taken and then double exposed to record the trace of the second line.

Appendix I shows Rutscher's results. His data were taken for the following conditions: pressure 1.4 torr; discharge tube current 100 ma; discharge tube diameter 6 cm; striation wavelength 9 cm and striation frequency 2320 Hz. His results indicate that the maxima in the transitions from the higher excitation levels occur first. This does not support the model postulated by Donahue and Dieke (3).

In our experiment Rutscher's conditions were matched as closely as possible, although signals from the 6402, 5944 and 6929A lines were the only signals strong enough to give meaningful data. The 6402A and 5944A lines were compared at a pressure of 1.4 torr and tube current of 142 ma. (This is the closest approach to Rutscher's experiment that could be obtained. The instabilities in the striations were too great to get any data at his exact conditions.) The 6402A and 5944A lines were also compared at pressures of 2.74 torr

and 4.45 torr for a number of discharge tube currents. The 6402A and 6929A lines were compared at a pressure of 4.45 torr and discharge tube currents of 150, 200 and 250 ma.

The relatively high uncertainty of the measured striation wavelength and frequency for the 6402A and 6929A line comparisons, was caused by relatively unstable striations. In general, the frequencies found in this experiment were on the order of 500 Hz while Rutscher's frequency was 2320 Hz. Rutscher reported a wavelength of 9 cm, while the wavelengths in our experiment were on the order of 11 cm at 4.45 torr and 16 cm at the lower pressures. There is some question as to what Rutscher's tube diameter was. In Rutscher's table of results he states the discharge tube conditions and lists R = 3 cm. We interpreted this to mean that the tube radius was 3 cm; however, the R may represent the first letter in the German word for tube diameter. Our tube diameter was 6.35 cm in diameter thinking that it closely approximated Rutscher's 6 cm diameter tube.

During the experiment the oscilloscope was kept in the chop mode and not the alternate mode between the two traces. The chopping is shown clearly in figure 4 and is of sufficiently high frequency as not to effect the data. The use of the chop mode eliminated the possibility of a phase shift being introduced by the oscilloscope. As previously stated, the equipment was capable of detecting a 2 microsecond phase shift. The pairs of lines that were compared were those which had been reported to have reasonably large phase shifts.

The single sweep mode of the oscilloscope was used in taking all the photographs. The use of this mode enables pictures to be taken even when the striations were somewhat unstable.

Measurements of striation frequency and wavelength were also made at various discharge tube parameters. The striation frequency was measured directly from the oscilloscope face using the horizontal sweep speed and the number of peaks per cm. This was done by using the trace obtained from the externally mounted photomultiplier tube, previously used for triggering. The wavelength was measured using another externally mounted photomultiplier tube which was movable. This second tube was mounted on a rack in such a manner that the amount that the tube was moved was measurable. The dual-trace oscilloscope was then used to compare the traces from the two externally mounted photomultiplier tubes. First the peaks of the two traces were aligned. Then the moveable photomultiplier tube was moved until the peaks of its trace had moved exactly the distance between the peaks of the stationary trace above it. The wavelength was then measured from the scale on the rack.

2. Results

Approximately 55 observations were made, each data point being the average of four to six observations. Within the experimental uncertainties shown in the table below, no phase shifts were observed. Figure 7 shows a typical photograph used, showing clearly that there is no discernible phase shift.

TABLE OF RESULTS

Differences in the Time at Which the Maxima Occurred

For the 6402A and 5944A Wavelengths

Discharge Tube Pressure (torr)	Discharge Tube Current (ma)	Phase Diff. of maxima (microseconds)	Striation Frequency (Hz)	Wavelength (cm)
1.4	142	0 ± 20	---	---**
2.74	100	0 ± 15	550 ± 10	15.80
	135	0 ± 10	---	---
	150	0 ± 15	533 ± 10	15.92
	200	0 ± 10	537 ± 10	16.41
	225	0 ± 20	542 ± 10	16.50
4.45	150	0 ± 20	---	---
	200	0 ± 10	---	---
	250	0 ± 20	---	---

Differences in the Time at Which the Maxima Occurred

For the 6929A and 6402A Wavelengths

4.45	150	0 ± 25	500 ± 25*	10.0 ± 1.0*
	200	0 ± 25	500 ± 25	11.1 ± 1.0
	250	0 ± 25	500 ± 25	11.0 ± 1.0

Slit size 750 microns

** Data not available

* Striations not stable enough to get more accurate readings.

3. Conclusions

The results of this experiment do not agree with Rutscher. However, it is possible that the two experiments studied different striation phenomena. Rutcher's striation wavelength was on the same order of magnitude as found in this experiment, while his striation frequency was four times greater. This implies that his striation velocities were approximately four times as great as the striation velocities found in this experiment. The difference in the striations might be due to differences in discharge tube geometry. The question of the possible difference in tube diameters has previously been explained. In addition Rutscher did not state his tube length. The diagram of Rutscher's experimental apparatus found on page 2 of his paper (13) shows the discharge tube to be shaped somewhat like an incandescent light bulb. Such differences in tube geometry would certainly cause some differences in the corresponding striations. In addition differences in the results may also have been caused by differences in the circuit supplying the potential across the tube since the external circuit plays an important part in the amplification mechanism of the striations.

More recent studies as reviewed by Oleson and Cooper (6), indicate that metastable states are not necessary for the production of fast moving striations. If the two-stage ionization process is not necessary, then the mechanism proposed by Donahue and Dieke is not a general model, and it follows that the lower excitation transitions need not occur

first. Furthermore it is entirely plausible that some other mechanism may be responsible for the lower excitation transitions lagging the higher excitation transitions as found by Rutscher in fast moving striations.

The occurrence of metastable states is prevalent in slow moving striations, so the Donahue and Dieke model may be accurate for this phenomenon, and the lower excitation transitions may be expected to lead in the slow striations.

Slow striations were studied in this experiment while Rutscher's results (Appendix I) are for fast striations. The difference in the results in the two experiments may therefore be reasonable. Since slow striations were studied in this experiment it might be expected that the lower excitation transitions would lead the higher excitation transitions as predicted by the Donahue and Dieke model. Within the experimental uncertainties of our experiment no phase shifts were noted. Small phase shifts may have existed but certainly phase shifts of 30 microseconds and larger did not occur.

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APPENDIX I

RUTSCHER'S RESULTS

Neon; p = 1.4 Torr; R = 3 cm; i = 100 ma; l = 9 cm; f = 2.32 KHz

Wavelength (A)	Excitation voltage (eV)	Phase shift (cm)
5852.5	18.96	1.14
5400.6	18.96	1.12
6598.9	18.72	0.54
6029.9	18.72	0.34
6074.3	18.71	0.49
6678.3	18.70	0.48
5944.8	18.70	0.46
6266.5	18.69	0.33
6929.5	18.63	0.36
6143.1	18.63	0.38
6532.9	18.61	0.20
6217.3	18.61	0.34
6334.4	18.57	0.19
6402.3	18.55	0.00
7032.4	18.38	0.15

APPENDIX II

EXPERIMENTAL APPARATUS

1. Vacuum System

A schematic diagram of the vacuum and filling system is shown in figure 8. The system consisted of the following equipment:

a. Type Ed-150 Edwards Speedivac Fore Pump.

b. Veeco 2" air cooled diffusion pump.

c. 2.5 liter copper trap attached to the top of the diffusion pump.

d. Granville-Phillips Company Type C ultra-high vacuum valve located between the pumping system and the filling manifold.

e. Alpert type VAU-25 ultra-high vacuum valve located at the entrance of the discharge tube.

System pressure measurements were made by two thermo-couple gauges, one located between the diffusion and fore pumps, the other located above the main cut-off valve; and a GCA Corporation BA 100N ionization guage located between the cold trap and the main cut-off which was controlled by a Veeco vacuum gauge, type RG-31A.

The system was capable of reducing the discharge tube pressure to 2 x 10^{-7} torr.

2. Discharge Tube and Gas Filling System

The discharge tube was a cylindrical pyrex tube with an overall length of 91 cm and a length between electrodes of

67.7 cm. The tube diameter is 6.35 cm. The electrodes at each end of the tube were identical and were made of tantalum.

In the initial stages of the experiment, the entire glass system was cleaned by heating the glass with heating tapes. The system was heated to temperatures on the order of 300°C while the vacuum system was operating. Pressures on the order of 2.5×10^{-7} torr were obtained with the system temperature at 300°C. The discharge tube elements were then outgassed using an rf induction heater. This outgassing was done while the system was still hot. At the completion of outgassing the elements, neon gas was admitted to the discharge tube and the elements were then cooled in the neon atmosphere. Final cleaning of the discharge tube was accomplished by running several discharges in the tube until stable striations were obtained.

After the system was baked-out, the filling manifold and discharge tube were isolated from the pumping system by closing an ultra-high vacuum valve. This eliminated all the metal parts of the system which might cause gas contamination through outgassing of these metal parts. The discharge tube was then filled with neon at the desired pressure and sealed off by closing the ultra-high vacuum valve located at the entrance of the tube.

3. Power Supplies

The following power supplies were used as indicated.

a. The discharge voltage was supplied by a Kepco Labs model 770B regulated voltage (0-600v DC, 3 amp)

power supply. The tube current was measured using the built-in ammeter in conjunction with another ammeter connected in the circuit.

b. An auxiliary Pupps discharge was maintained at the anode by a Kepco Labs model 500B regulated voltage (0-600v DC, 300 ma) power supply.

c. A Power Designs Pacific Inc. model HV-1565, regulated voltage power supply (1-2000v DC, 15 ma) supplied power to two RCA 7102 photomultiplier tubes mounted in the spectrograph.

d. A Harrison Model 6515A (0-1600v DC, 0-5 ma) supplied power to an RCA 1P21 photomultiplier tube which was used to provide an oscilloscope triggering signal.

4. Spectrograph and Measuring Instruments

A schematic diagram of the physical arrangement of the equipment is given in figure 9. The light emitted from the discharge passed through the adjustable slit, through the lens and was focused on the 750 micron entrance slit of the spectrograph.

The spectrograph was a Baird-Atomic Plasma Spectrograph with a three meter concave grating (on an ~~eagle~~ E mount), ruled with 15,000 lines per inch. The discharge tube was mounted perpendicular to the optical axis of the spectrograph.

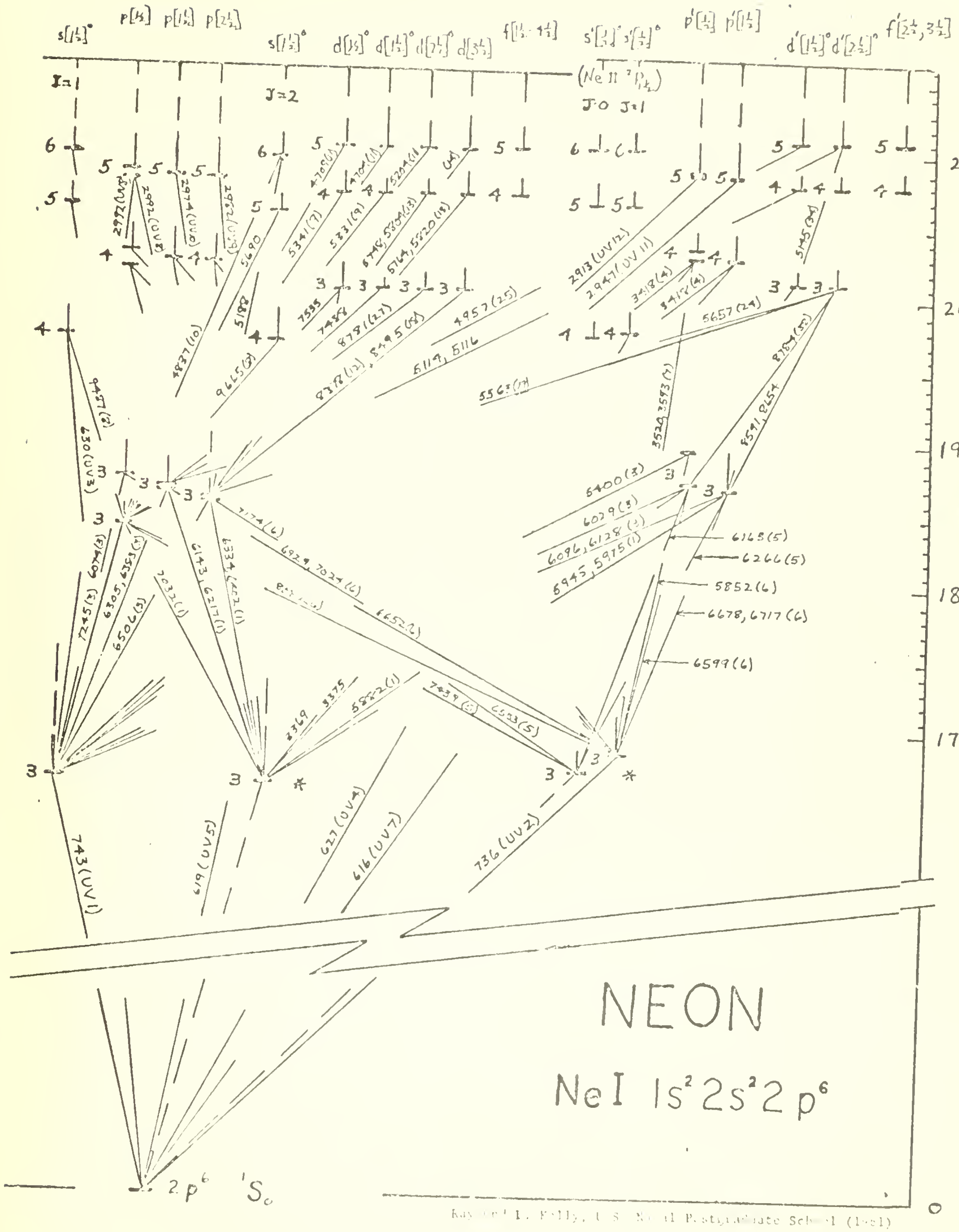
Two RCA photomultiplier tubes were mounted in a rack in the front of the spectrograph. The signal outputs of these photomultiplier tubes were fed to the input of a Tektronix

type 1A1 plug-in preamplifier (12.5 nanosecond rise time). The pre-amp inputs were loaded by connecting 5.1 megohm resistors in parallel across the inputs. This value of resistance provided the maximum signal strength on the oscilloscope. The preamplifier was plugged into a Tektronix type 547 dual-trace oscilloscope.

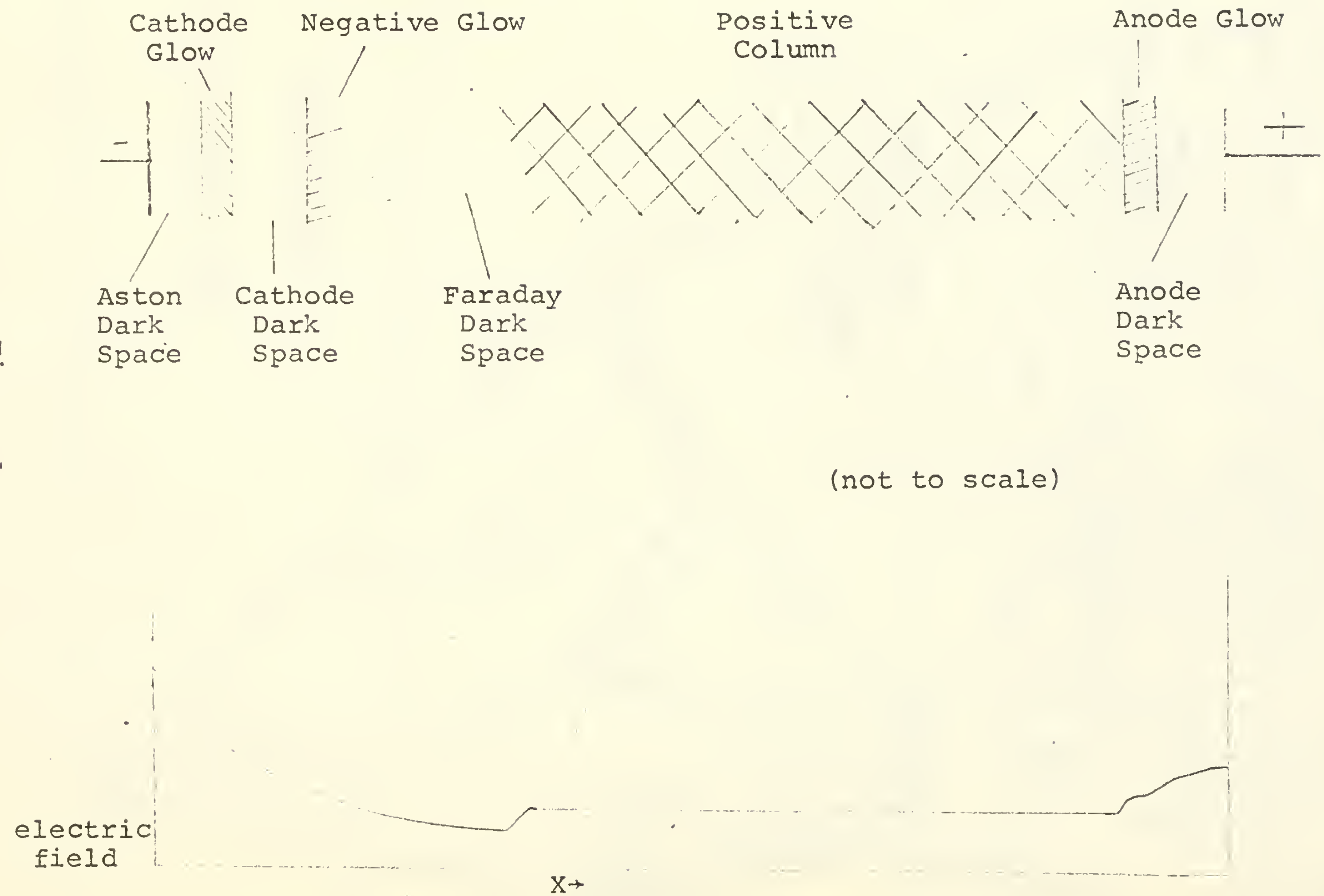
5. Miscellaneous

An RCA 1P21 type photomultiplier tube was used to provide a triggering signal to the oscilloscope, and was connected directly to the trigger input.

The neon gas used was manufactured by the Linde Division of the Union Carbide Corporation.



Raymond L. Kelly, U.S. Naval Postgraduate School (1961)



A Glow Discharge

Figure 1

Discharge tube current-voltage characteristic

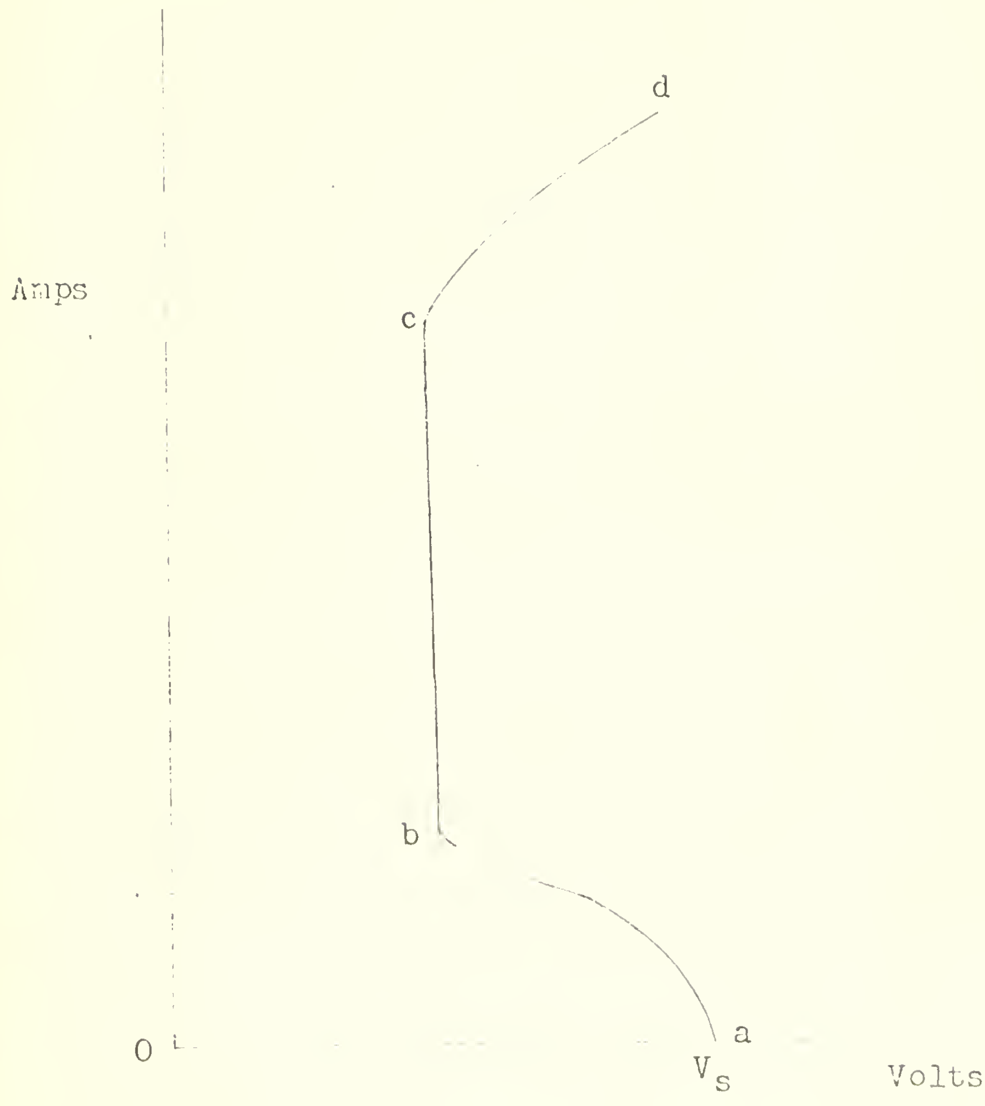
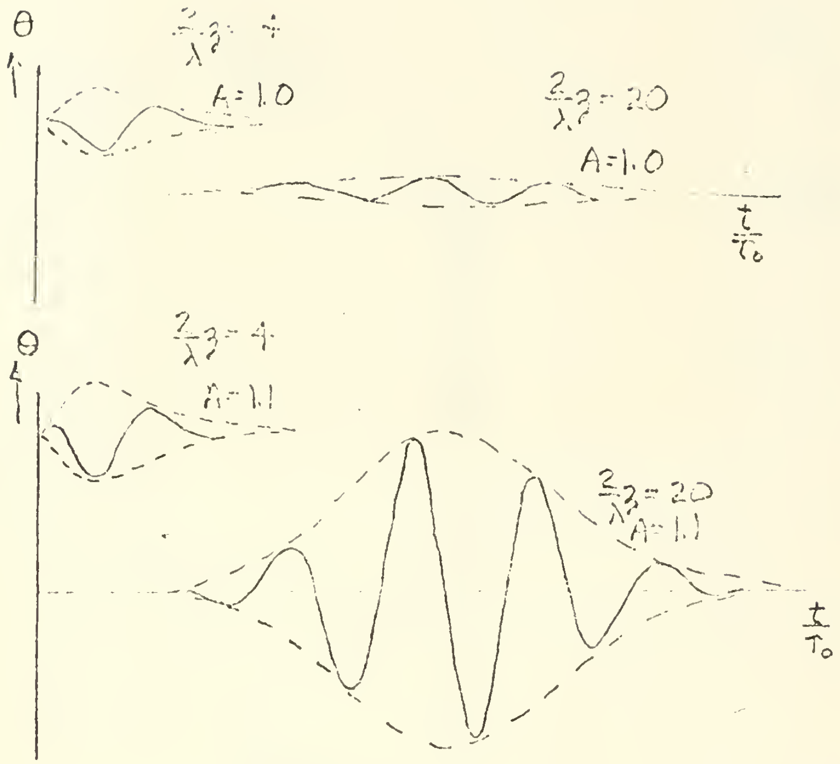


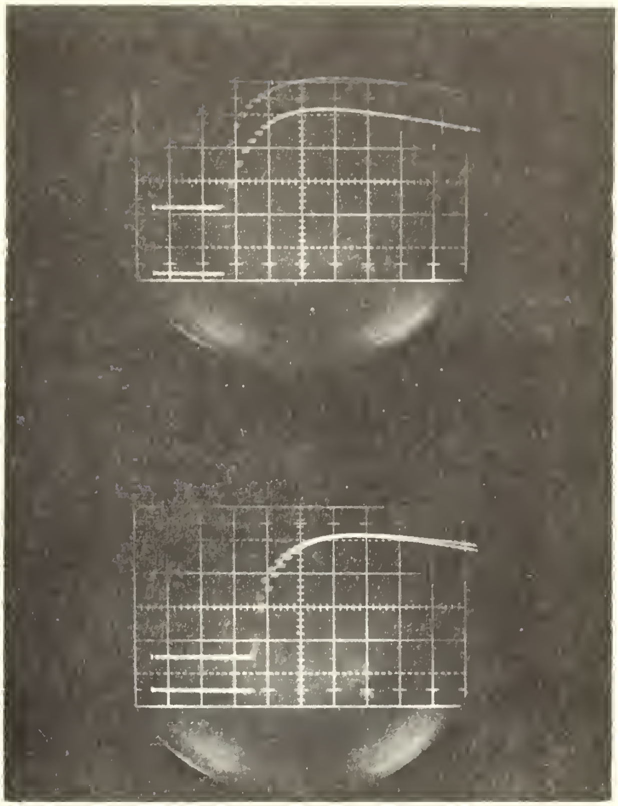
Figure 2



Packet of stratification

Plot of equation (3)

Figure 3

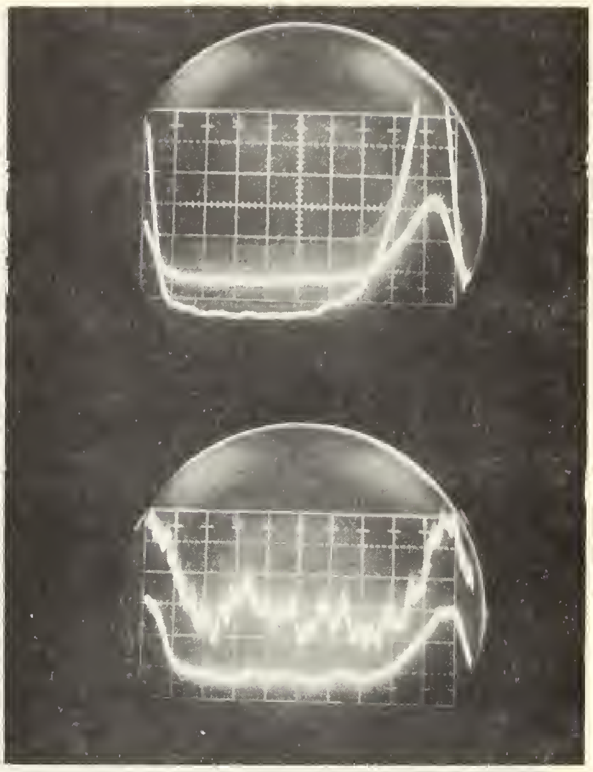


System response to strobe light

Source - strobe light [illegible]00 Hz

Horizontal sweep speed [illegible] microseconds/cm

Figure [illegible]



Effect on the signals of cooling the PM tubes

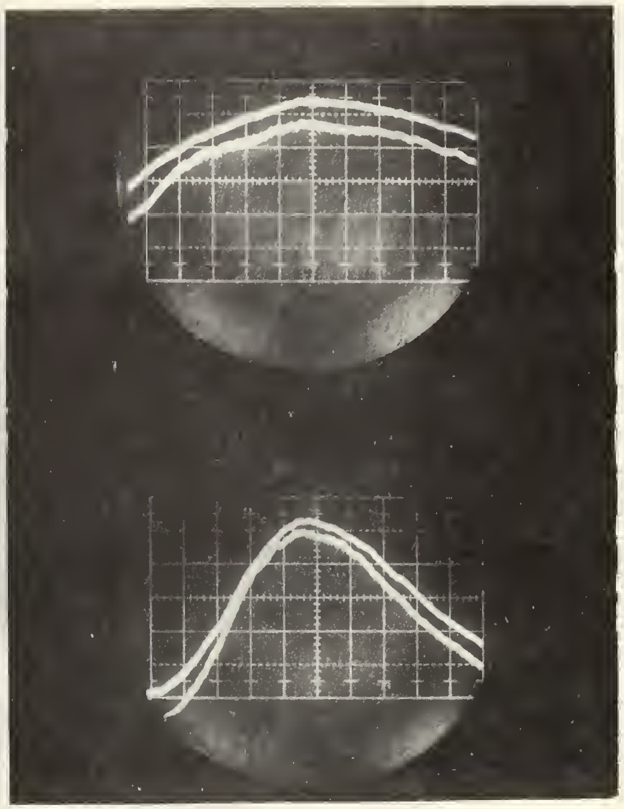
Both photographs were taken for identical discharge tube conditions, oscilloscope settings and the same signals were used. The bottom photograph was taken before the PM tubes were cooled with liquid nitrogen, the top photograph after cooling.

Figure 5

PM tube cooling apparatus

The two hoses going off to the right of the photograph carry liquid nitrogen to the faces of the PM tubes.

Figure [illegible]



Discharge tube pressure 2.74 torr.

Discharge tube current 135 ma.

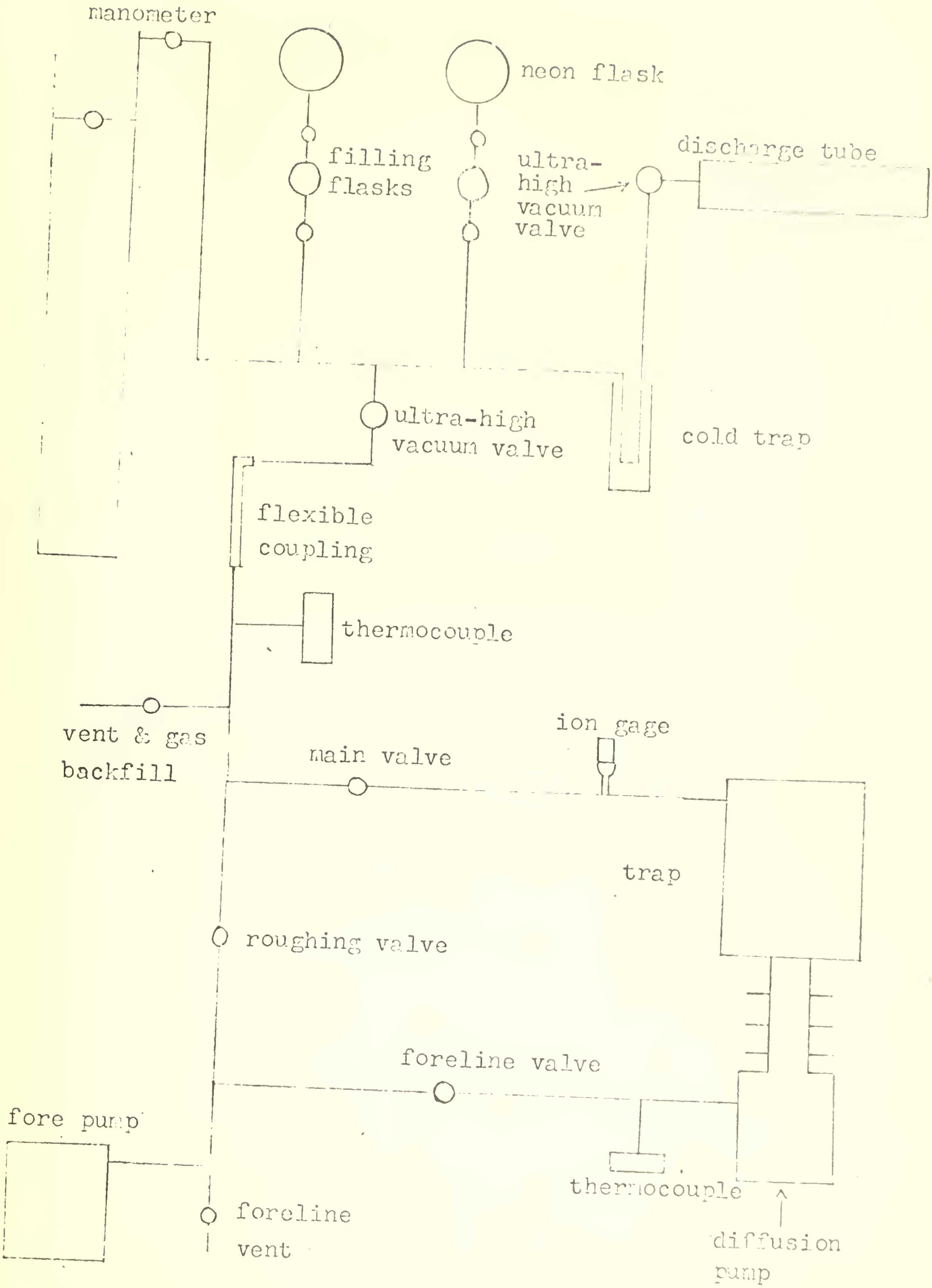
Upper trace 6402A line.

Lower trace 5944A line.

Top picture sweep speed 20 microseconds/cm.

Bottom picture sweep speed 50 microseconds/cm.

Figure 7



Vacuum system

Figure 8

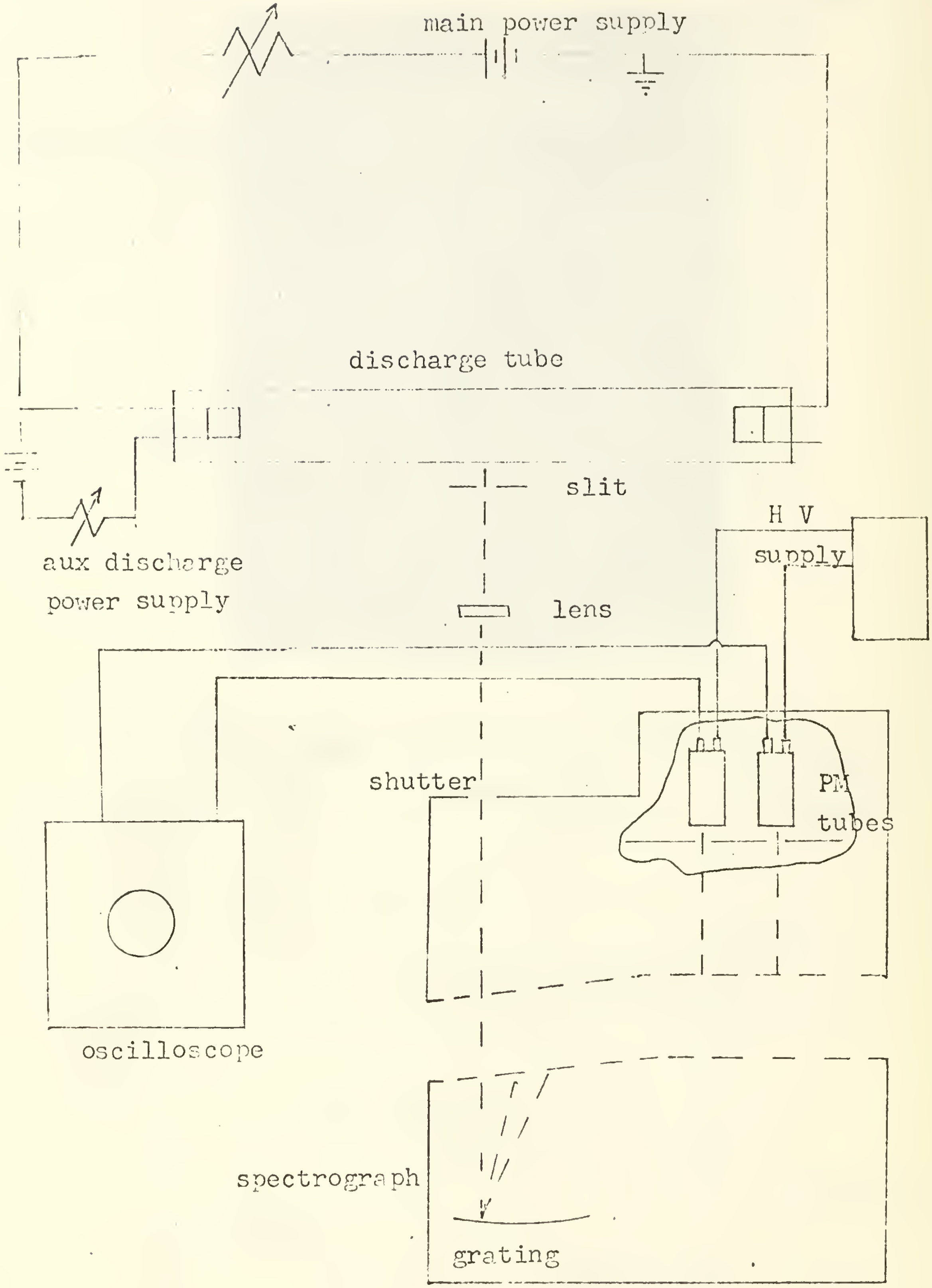


Figure 9

Equipment diagram

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13. ABSTRACT

An investigation of moving striations in a neon glow discharge, using a Baird-Atomic Plasma Spectrograph, was conducted to determine the time difference in the occurrence of the maxima of the neon spectral lines. Data are presented in the form of oscilloscope trace photographs. These photographs were analyzed to determine the time differences in the occurrence of the maxima of the 6402A and 5944A lines and the 6402A and 6929A lines of neon. Discharge tube pressures of 1.4, 2.74 and 4.45 torr were used with a variation of discharge tube current at each pressure. No time differences were observed within an uncertainty of approximately 15 microseconds.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
NEON GLOW DISCHARGE						
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MOVING STRIATIONS						

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